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A review of reliable and energy efficient direct torque controlled induction motor drives

C.M.F.S. Reza *, Md. Didarul Islam, Saad Mekhilef *

Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, University of Malaya, Kuala Lumpur, Malaysia

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A B S T R A C T

For a reliable dynamic system and significant amount of savings in energy usage, adjustable speed drives (ASD) can play a vital role. The proper control of motor drives can give a good system response and also increase the efficacy of the drive. Recently the direct torque control (DTC) strategy has drawn great attention for motor drives due to its simplicity, insensitivity to the motor parameters, high reliability and improved dynamic response. Many control strategies have been developed for the improvement of conventional DTC drives focusing specifically on torque and flux. A number of techniques have been formulated and successfully implemented for induction motor (IM) control. This paper aims to provide a substantial updated review, albeit by no means complete, for those who are interested in keeping track of the present state-of-the-art in this field and working further. The review focuses on different control algorithms of DTC IM drives and their applications to minimize the energy losses and improve the system efficacy.

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* Corresponding authors at: Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia.
E-mail addresses: sushan_hbk@yahoo.com, sushan_hbk@siswa.um.edu.my (C.M.F.S. Reza), didarul@gmail.com (Md.D. Islam), saad@um.edu.my (S. Mekhilef).

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Nomenclature

ASD	adjustable speed drives
AC	alternating current
CPWM	continuous PWM
DSP	digital signal processor
DTC	direct torque control
DSVM	discrete SVM
DPWM	discontinuous PWM
DTNFC	direct torque neuro fuzzy control
DSC	direct self control
DC	direct current
FOC	field oriented control
FLC	feedback linearization control
FDTC	fuzzy based DTC
GDPWM	generalized DPWM
IM	induction motor
IGBT	insulated gate bipolar transistor
PBC	passivity based control
I_{sd}, I_{sq}	stator current component in $d-q$ coordinate system
I_{sd^s}, I_{sq^s}	stator current component in d^s-q^s coordinate system
MLI	multilevel inverter
MC	matrix converter
PMSM	permanent magnet synchronous motor
PWM	pulse width modulation
SMC	sliding mode control
SVM	space vector modulation
T_r	torque reference
VSC	variable structure control
V_{sd^s}, V_{sq^s}	stator voltage component in d^s-q^s coordinate system
V_{sd}, V_{sq}	stator voltage component in $d-q$ coordinate system
Ψ_{sd^s}, Ψ_{sq^s}	Stator flux component in d^s-q^s coordinate system
Ψ_{rd^s}, Ψ_{rq^s}	Rotor flux component in d^s-q^s coordinate system
ω_r	Speed reference

1. Introduction

Adjustable speed drives (ASDs) are normally used in the industry. Generally, induction motors (IMs), and, recently, permanent magnet synchronous motors (PMSMs) are used in these drives. Variable speed drives are mainly used in applications, such as electrical vehicles, pumps, elevators, fans, ventilation, heating, robotics, ship propulsion, and air conditioning [1,2].

Previously, DC motors were normally used for adjustable speed drives. However, due to the disadvantages of the DC motors, such as necessity of maintenance, sparks and corrosion, in the last thirty years DC machines have been progressively replaced by AC machines. This is because of the developments in semiconductor device technology, mainly power insulated gate bipolar transistor (IGBT) and digital signal processor (DSP) technologies [3–5].

According to the statistics three phase IMs are extensively used in industry and consume more than 60% of industrial electricity [2,6]. Therefore, using reliable and highly efficient IM drives can undoubtedly result in more economical drives that can significantly help in saving energy. The performance of IM drives mainly depends on the type of control strategy employed. The main objective of choosing a particular control scheme is to utilize the best possible parameters for the drive. The simplicity of the controller is also a major concern. These methods are mainly divided into vector based and scalar based controllers.

Scalar based control is easy to implement. Although the constant voltage/frequency control method is the simplest, the performance of this method is not good enough [7–9]. Vector based control methods allow the control of amplitude of voltage and frequency unlike in scalar based control methods. They also provide the instantaneous position of the current, voltage and flux vectors [7–10]. The dynamic behaviour of the IM drives is also improved significantly by the use of the vector based control method. However, the existence of the coupling between the electromagnetic torque and flux increases the complexity of the controller. To deal with this inherent disadvantage, several methods have been proposed for the decoupling of the torque and flux. In the later part of this section some of these methods have been introduced.

Field oriented control (FOC) was originally proposed by Blaschke (direct FOC) [11] and Hasse (indirect FOC) [12]. Many researchers have investigated these methods [13–30] and now it has become an industry standard. Motor equations are transformed into a coordinate system, which rotates synchronously with rotor flux in the FOC method [16,30–32]. The FOC method ensures torque and flux decoupling in spite of the presence of nonlinearity in the IM equations.

Feedback linearization control (FLC) is another method that introduces new nonlinear transformation of induction motor state variables. In this coordinate system rotor flux and speed are decoupled by the use of feedback [33,34]. A method based on energy shaping and variation theory has been proposed, which is known as passivity based control (PBC) [35]. In this method, Euler–Lagrange equations are expressed in the generalized coordinates and used to describe the induction motor.

However, the FOC technique is complex because it requires reference frame transformation and is dependent on the mechanical speed and motor parameters. To overcome these difficulties and control the torque of the induction motor, new techniques have been proposed—direct torque control (DTC), by Takashi and Noguchi [36], and direct self control (DSC), by Depenbrock [37–39]. To replace motor decoupling and linearization by means of coordinate transformation the authors proposed new strategies like FOC by hysteresis controller, which corresponds very well to the on-off operation of the inverter. These strategies are known as classical DTC. The major limitation of DTC is large flux and torque ripples compared to FOC. Another drawback of the conventional DTC is the non-constant switching frequency of the inverter, which varies with load torque, rotor speed and the bandwidth of the hysteresis controllers. Many attempts have been taken to overcome these limitations in the last few decades [40].

This paper reviews different control schemes proposed so far to achieve high efficient DTC-IM drive system. After that application of DTC drive such as in electric vehicle, wind energy conversion system to extract maximum power, industry sector to minimize energy losses and increase the system efficacy are presented.

2. Adjustable speed drives

By proper controlling the motor adjustable speed drives can reduce energy losses. Many control schemes have been proposed so far is based on the motor model equation. In this section induction motor model equation is discussed and then scalar and field oriented control technique discussed briefly.

2.1. Induction motor model

When a three phase induction motor is modelled by mathematical equations [41] it is assumed that the motor is a symmetrical

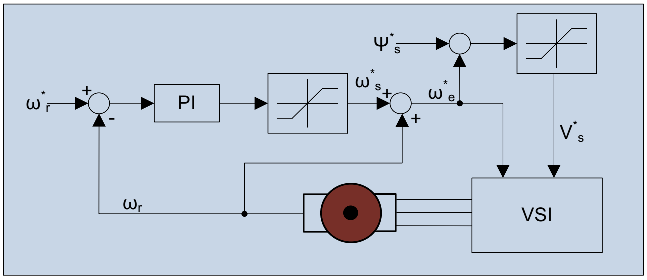

Fig. 1. Closed loop scalar controlled induction motor drive.

three phase motor and the rotor and stator windings are replaced by a concentrated coil. Only the fundamental harmonic is considered and all other losses except core loss and friction loss are ignored. For mathematical simplicity it is also considered that the coil resistance and reactance are invariant.

Motor model equations can be expressed in d^s-q^s coordinate system as:

$$V_{sd^s} = R_s I_{sd^s} + \frac{d\Psi_{sd^s}}{dt} \tag{1}$$

$$V_{sq^s} = R_s I_{sq^s} + \frac{d\Psi_{sq^s}}{dt} \tag{2}$$

$$0 = R_r I_{rd^s} + \frac{d\Psi_{rd^s}}{dt} + p\Omega_m \Psi_{rq^s} \tag{3}$$

$$0 = R_r I_{rq^s} + \frac{d\Psi_{rq^s}}{dt} - p\Omega_m \Psi_{rd^s} \tag{4}$$

$$\Psi_{sd^s} = L_s I_{sd^s} + L_M I_{rd^s} \tag{5}$$

$$\Psi_{sq^s} = L_s I_{sq^s} + L_M I_{rq^s} \tag{6}$$

$$\Psi_{rd^s} = L_r I_{rd^s} + L_M I_{sd^s} \tag{7}$$

$$\Psi_{rq^s} = L_r I_{rq^s} + L_M I_{sq^s} \tag{8}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}\left[p\frac{m_s}{2} I_m(\Psi_{sd^s} I_{sq^s} - \Psi_{sq^s} I_{sd^s}) - T_L\right] \tag{9}$$

These equations are the basis for designing the controller for a motor drive. However, these equations are not adequate for designing the control structure, because the output speed, torque and flux depend on both inputs. From this point of view, the system is complex. For this reason some methods have been proposed for decoupling the torque and flux control, which will be discussed in the next section.

2.2. Scalar control IM drive

This control scheme focuses on the steady state dynamic only. This technique, as shown in Fig. 1, is used for controlling the motor speed based on the frequency and magnitude of the voltage applied. This is done in such a way that the flux air gap flux is always maintained at the desired steady state value. This scheme is established based on the per phase steady state equivalent circuit of IM with a goal preserving constant magnetizing current by changing the applied voltage magnitude proportional to the frequency applied. The constant *V*/*f* is an example of the scalar control scheme of IM.

Based on the constant V/Hz principle, both the open and closed-loop control of the speed of an AC induction motor can be implemented. When accuracy in the speed response is not required the open-loop speed control is used, for example, in HVAC (heating, ventilation and air conditioning), fan or blower applications.

This scheme is not capable of controlling torque and flux, which are the most essential variables in IMs [2,42]. Therefore, this scheme cannot be applied where precise control of torque is mandatory. The main limitations of this scheme are poor response of torque and the speed accuracy is not good enough, particularly at the low speed operating region.

2.3. Field oriented control

The idea for the field oriented control (FOC) was first discovered by Blaschke [11]. He checked how orientation of field takes place normally in the separately excited dc motor. The field fluxes and armature are always perpendicular. In the induction motor, a similar condition to that stated above can be produced with proper control of the stator current in a synchronously rotating reference frame.

In the FOC, the stator current is decoupled into two components, one produces the torque and the other produces the flux. This gives independent control of the flux and torque during both the steady state and dynamic condition. This is possible in the case where the co-ordinate system is associated with the flux vector of rotor.

Coordinate transformation is the main landmark of the FOC method. Measurement of the current vectors is done in the d^s-q^s stationary coordinate. Therefore, the current vectors I_{sd^s} and I_{sq^s} must be converted into the $d-q$ rotating system. Similarly, the stator voltage components reference$V_{sd^s r}$ and $V_{sq^s r}$ must be converted from $d-q$ to the d^s-q^s coordinate system. The angle of rotor flux (θ_{sr}) is required for these transformations. Depending on the angle calculation, two different types of FOC methods can be considered. Those are the indirect field oriented control (IFOC), shown in Fig. 2, and the direct field oriented control (DFOC) method.

The angle of rotor flux (θ_r) is found from the I_{sdr} and I_{sqr} reference currents in the IFOC method. The angular speed of the rotor flux vector is found as follows:

$$\Omega_{sr} = \Omega_{sl} + p\Omega_m \tag{10}$$

Here slip speed (Ω_{sl}) is

$$\Omega_{sl} = \frac{1}{I_{sdr}}\frac{R_r}{L_r} I_{sqr} \tag{11}$$

An observer or estimator is used to calculate the angle of rotor flux θ_r in the DFOC method. The stator currents or voltages are the inputs to the observer or estimator. A block diagram of the DFOC method is given in Fig. 3. In both cases, the reference currents I_{sdr} and I_{sqr} in the rotating coordinate reference are calculated using the reference torque and flux values.

In summary, these methods are considered as analogous to the DC motor control, which does not ensure an accurate flux and torque control decoupling in steady state and dynamic operation. A linear relationship exists between the control variables and regulated values when the rotor flux is constant, but full information for the load torque and state variables of the motor is required with the transformed current controller. Other FOC methods like the DFOC also require a flux observer, whereas a speed transducer is required in the IFOC.

3. DTC-IM drive

Direct torque control (DTC) induction motor drive is becoming more popular day-by-day due to its fast dynamic response and

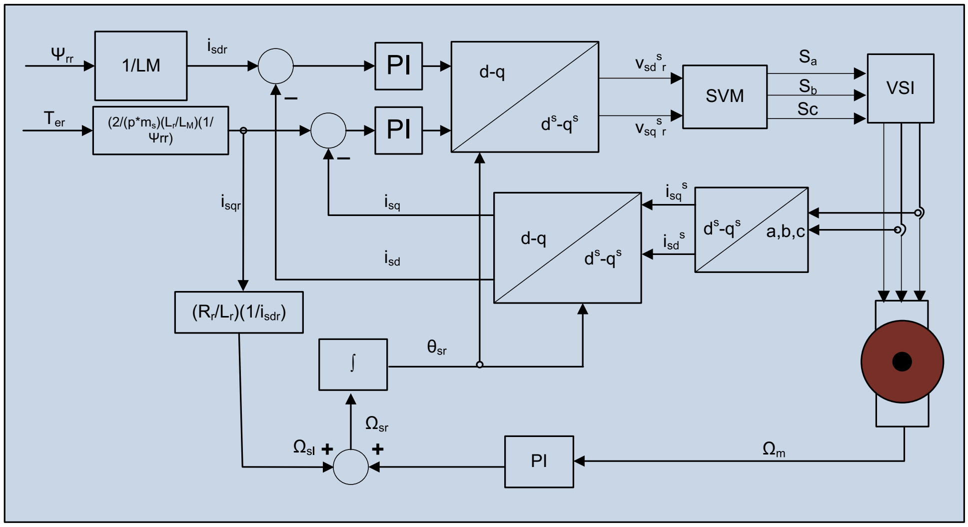

Fig. 2. Indirect field oriented control (IFOC) block diagram.

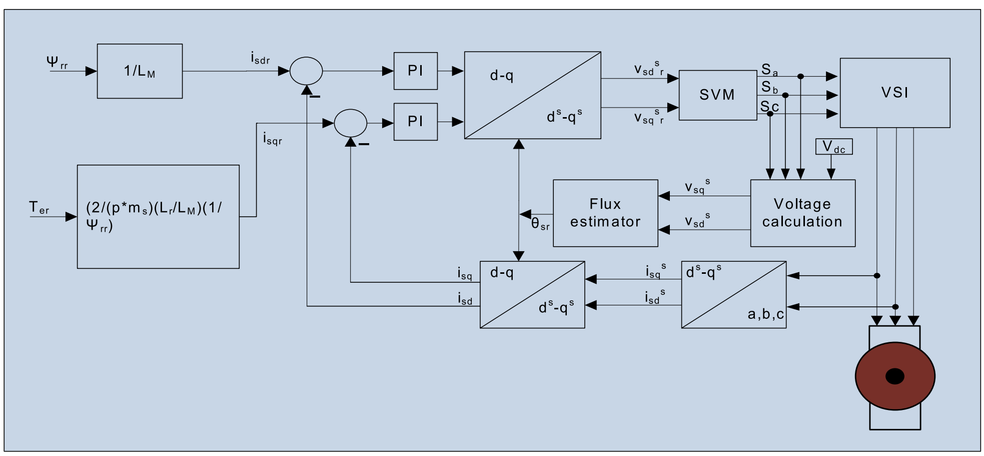

Fig. 3. Direct field oriented control (DFOC) method block diagram.

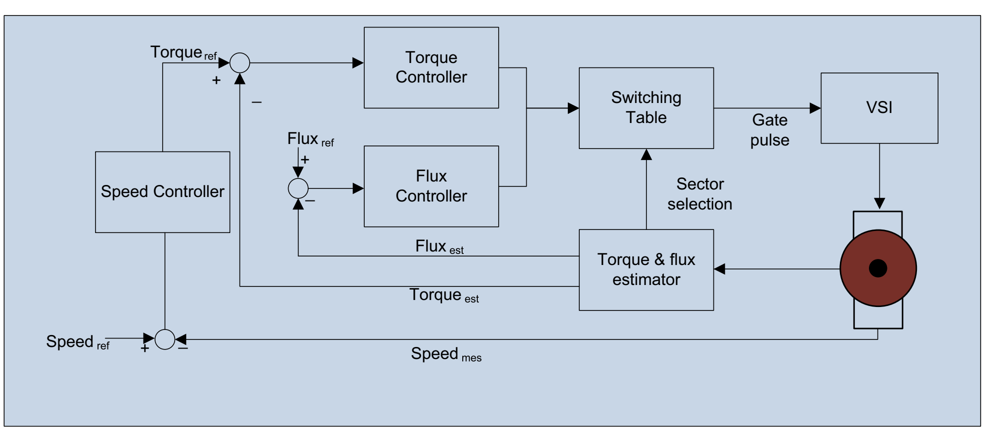

Fig. 4. Basic IM-DTC drive.

robustness to the variation of the machine parameter without using the current controller [36,38,43–49,163]. The implementation of this control strategy is very simple, and, in addition, coordinate transformation is not required.

In the basic DTC shown in Fig. 4, the errors of the electromechanical torque and stator flux status are detected and then passed through the hysteresis comparator (two and three level) for digitization. Then a predetermined switching table (Table 1) determines the status of the inverter switches, which will be used to determine the location of the voltage vector (V_s), which is selected according to the flux angle of the stator.

Although this makes the torque response faster, a torque ripple and variation of inverter switching frequency also exists. Later voltage sectors have been subdivided to deliver accurate voltage vectors [50–52]. However, the reduction in torque ripple is not good enough because of the sectors transition. Therefore,

researchers have proposed many DTC schemes for induction motor drives, which can be categorized as shown in Fig. 5. As we can see from Fig. 5 the DTC control strategy is primarily divided into two main classes, namely, the Typical and Modern DTC scheme. The following section discusses a further subdivision of the two classes above.

3.1. DTC-SVM

The concept of DTC-SVM for IMs was first introduced by Habetler [53]. Basic concept of SVM is the adjustment of flux speed by zero voltage vector insertion for controlling the generated electromagnetic torque by IM. By delivering the accurate voltage vectors applying the SVM strategy, flux and torque ripple and also non-constant switching frequency problem can be overcome effectively using similar hardware topology to that used in conventional DTC [54–56]. Various DTC-SVM strategies have been addressed depending on the reference voltage vector generation and SVM implementation.

3.1.1. DTC-SVM strategy using closed loop flux control

This technique utilizes stator flux components as the control variables. In this scheme the reference voltage vector is calculated at every sampling period based on the error between the reference and estimated voltage stator flux [57]. This scheme may be considered as a development of the DTC scheme, and aims to achieve constant inverter switching frequency.

In this type of control, as shown in Fig. 6, the rotor flux is used as Ref. [58]. The reference d and q axis stator flux in rotor flux coordinate Ψ_{sdr} and Ψ_{sqr} can be found using the following equation:

$$\Psi_{sdr} = \frac{L_s}{L_m}\left(\Psi_{rc} + \sigma \frac{d\Psi_{rr}}{dt}\frac{L_r}{R_r}\right) \tag{12}$$

Table 1
Switching table.

$\Delta\psi_s$	ΔT	S_1	S_2	S_3	S_4	S_5	S_6
	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_7	V_0	V_7	V_0	V_7	V_0
	−1	V_6	V_1	V_2	V_3	V_4	V_5
	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_0	V_7	V_0	V_7	V_0	V_7
	−1	V_5	V_6	V_1	V_2	V_3	V_4

$$\Psi_{sqr} = \frac{2}{pm_s}\frac{L_r}{L_m}\sigma L_s \frac{T_{er}}{\Psi_{rr}} \tag{13}$$

Therefore, the stator flux reference can be calculated as given below

$$\Psi_{sr} = \sqrt{\left(\frac{L_s}{L_m}\Psi_{rr}\right) + \left(\frac{2}{pm_s}\right)^2 (\sigma L_s)^2 + \left(\frac{L_r}{L_m}\frac{T_{er}}{\Psi_{rr}}\right)^2} \tag{14}$$

Stator flux reference value Ψ_{sdr} and Ψ_{sqr} are being compared with estimated values $\Psi_{s\alpha}$, $\Psi_{s\beta}$ after transformation of α–β coordinate system.

The reference voltage depends on the incremental value of the stator flux $\Delta\Psi_s$ and voltage drop across the stator resistance R_s.

$$V_{sr} = \frac{\Delta\Psi_s}{T_s} + R_s I_s \tag{15}$$

In the DTC-SVM, the magnitude of the rotor flux is regulated. Thanks to previous researchers, increasing the capability of the torque overload is possible [58,59].

However the main drawback of this strategy is that all parameters are required and it is sensitive to any variation among them.

3.1.2. DTC-SVM strategy using closed loop torque control

This technique for DTC is mainly based on control of the load angle, and it significantly addresses the important limitation of the conventional DTC [60,61]. In the conventional DTC, selection of the stator voltage is done by the hysteresis comparator in which the flux and torque error work as inputs and a predefined switching table is used to select the accurate voltage vector to implement the desired action. In this control scheme, the appropriate voltage vector is selected, which changes the stator flux to meet the load angle reference criteria.

This type of control method was primarily proposed for permanent magnet synchronous motors (PMSM) [62,63]. However, as the basics of DTC for PMSM and IM are identical, this method can be applied for IM [64]. The block diagram of this control method of DTC-SVM is given in Fig. 7.

A PI controller is used to regulate the torque. The increment of the torque angle $\Delta\delta_\Psi$ (Fig. 7) is the output of the PI controller. In this fashion, the torque is regulated by changing the angle between the rotor and stator fluxes similar to the basic DTC.

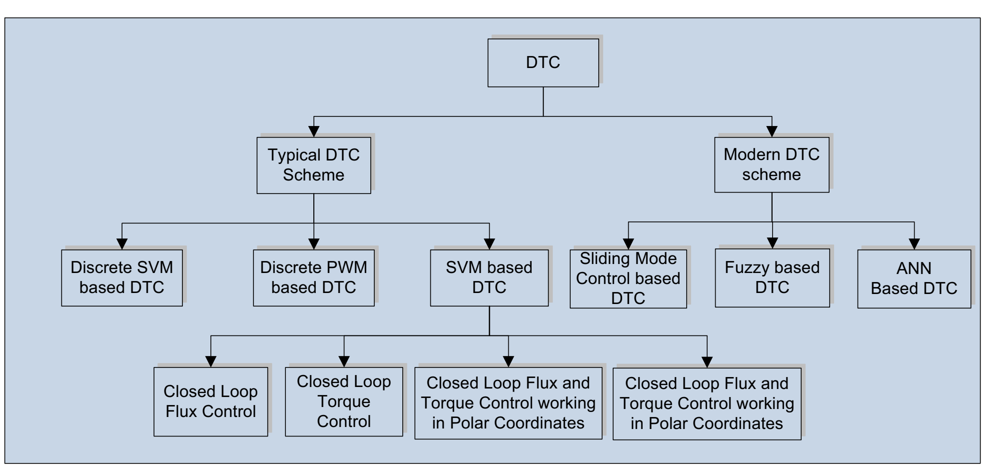

Fig. 5. Classification of DTC schemes for the induction motor.

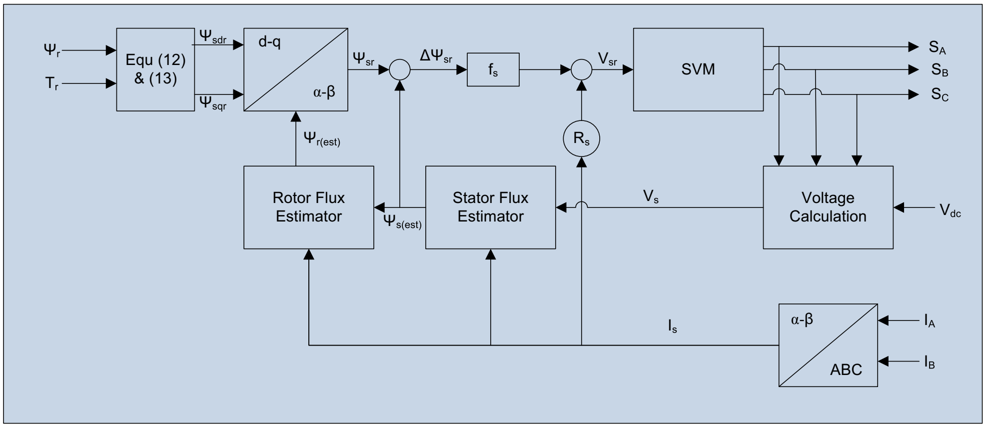

Fig. 6. DTC-SVM Strategies using closed loop flux control [56].

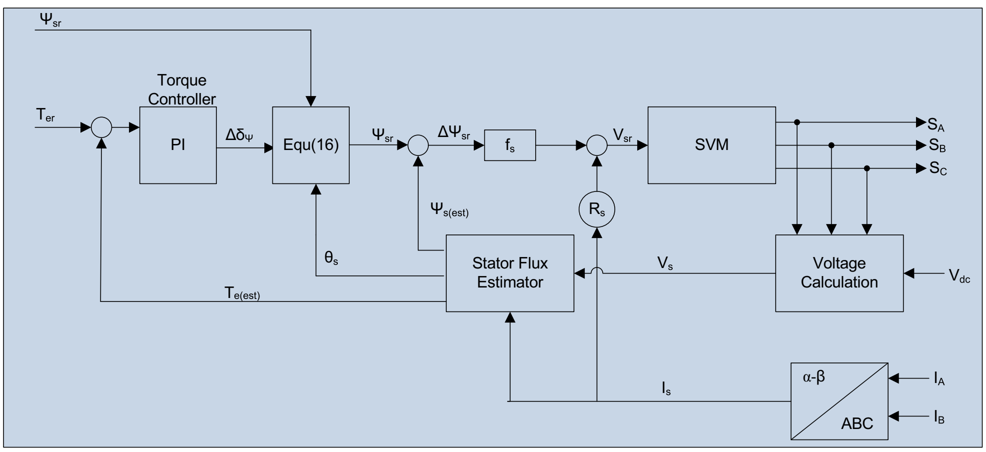

Fig. 7. DTC-SVM Strategies using closed loop torque control [64].

The stator flux reference is found from the following equation:

$$\Psi_{sr} = |\Psi_{sr}| e^{j(\theta_s + \Delta\delta_\Psi)} \quad (16)$$

The reference stator flux is then compared with the estimated value. To calculate the voltage reference, flux error $[\Delta\Psi_{sr} = (\Psi_{sr} - \Psi_{s(est)})]$ is used. The structure of this method is simple because it only has one PI controller, which makes the procedure easier to tune.

3.1.3. DTC-SVM strategy using closed loop flux and torque control working in polar coordinates

When both the flux and torque are being controlled in closed loop fashion, then the scheme provides further development. The strategy for operating in the polar coordinate is shown in Fig. 8 [65].

The stator flux error $\Delta\Psi_s$ is computed from outputs $\Delta\theta_s$ and k_Ψ of the torque and flux controller, as given below:

$$\begin{aligned} \Delta\Psi_s(k) &= \Psi_s(k) - \Psi_s(k-1) \\ &= ([1 + k_\Psi(k)] e^{j\Delta\theta_s(k)} - 1)\Psi_s(k-1) \end{aligned} \quad (17)$$

Assume that

$$e^{j\Delta\theta_s(k)} = 1 + j\Delta\theta_s(k) \quad (18)$$

Therefore, Eq. (17) can be written in the following form

$$\Delta\Psi_s(k) = ([k_\Psi(k) + j\Delta\theta_s(k)]\Psi_s(k-1)) \quad (19)$$

The reference stator voltage is computed according to Eq. (13). For improvement of the dynamic performance of the torque controller, the increment for angle $\Delta\theta_s$ is composed of two parts: the static part $\Delta\theta_{ss}$ is delivered by the feed forward loop and the dynamic part, $\Delta\theta_{sd}$, is generated by torque controller. When both torque and flux magnitudes are controlled in a closed-loop way, the strategies provide further improvement [67].

3.1.4. DTC-SVM scheme with closed loop torque and flux control in stator flux coordinates

The DTC-SVM scheme with closed loop flux and torque control in stator flux coordinates is presented in block diagram Fig. 9 [68]. The PI flux and torque controller outputs are the stator voltage components reference V_{sxr} and V_{syr} in the x–y coordinate. Then, these dc voltages are transformed into α–β stationary frame. After that, the transformed voltages, $V_{s\alpha r}$ and $V_{s\beta r}$, are supplied to the SVM.

Researchers have modified the SVM technique based on recently proposed power electronic schemes to achieve better performance as well as to improve the control system efficiency. Hybrid space vector PWM (HSVPWM) schemes are proposed in [69,70] to reduce switching loss and current ripple.

DTC based on five zones HSVPWM, has been addressed in [72] to reduce the flux and torque ripple. In 2006, seven zones HSVPWM were introduced for the DTC drive [73]. A new voltage modulation scheme has been addressed in [74] to reduce continuous SVPWM computational burden using effective time concept. For avoiding the sector, reference voltage and angle determination

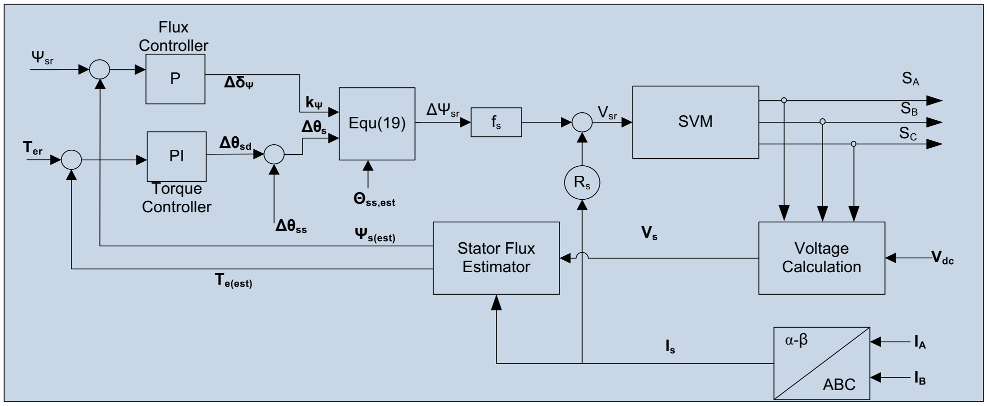

Fig. 8. DTC-SVM closed loop torque and flux control in polar coordinates [63].

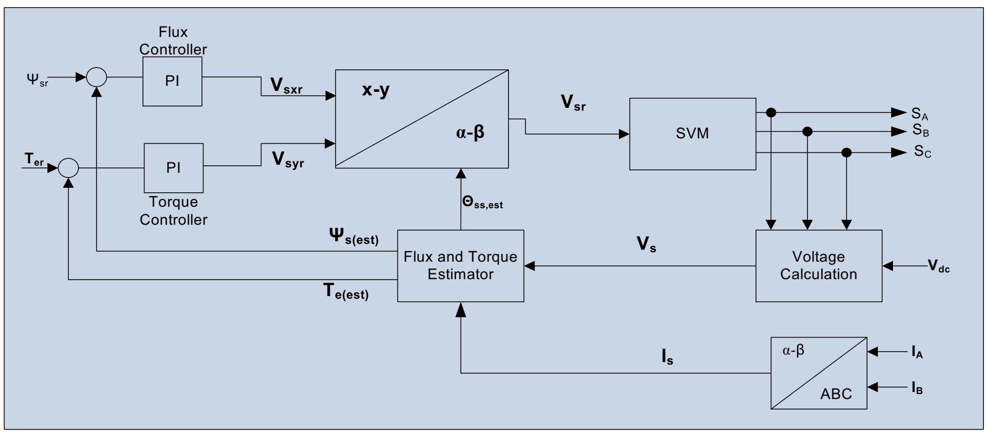

Fig. 9. DTC-SVM closed loop torque and flux control in stator flux coordinate [69].

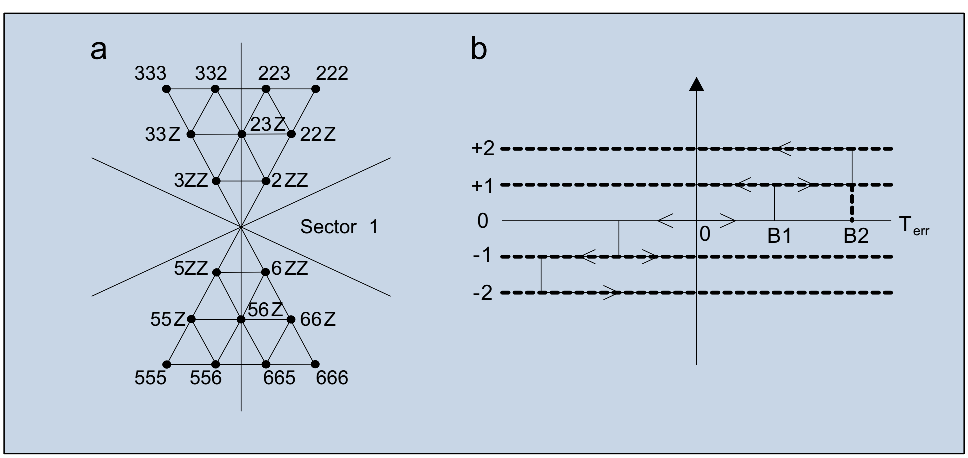

Fig. 10. (a) Voltage vectors found by the use of DSVM (b) torque hysteresis comparator (five-level) [75].

requirements, effective time has been calculated using the imaginary switching time concept in [75] and then the concept has been used for the different switching patterns. However, a comparatively complex calculation for the equation of the stator voltage is required, which is given in quadratic form in the stationary frame.

3.1.5. DTC using discrete SVM

The discrete SVM (DSVM) technique was developed for reducing the switching frequency using predefined time intervals in a period of cycles [76,77]. Using this concept it is possible to synthesize more voltage vectors compared to those utilized in the conventional DTC. More voltage vector generation allows the construction of an accurate switching table in which voltage vector selection is accomplished according to rotor speed, flux and torque error.

As presented in Fig. 10, three same time intervals have been utilized in a cycle period. The voltage vector selection is only done once in every sampling period. The advantage of this scheme is that it is possible to select among 19 vectors instead of 5 in the conventional DTC. Also, the same vectors enable torque variation

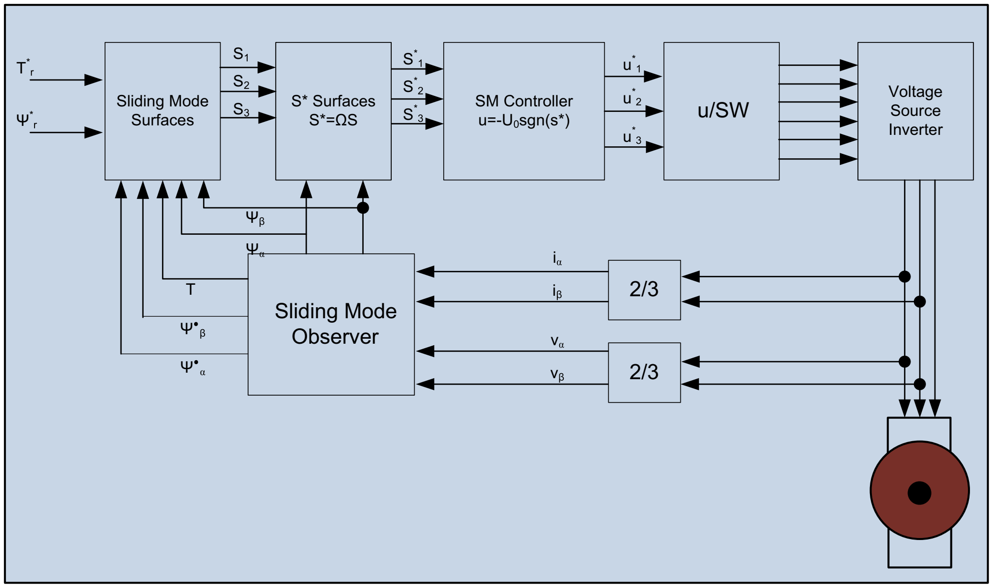

Fig. 11. Sliding mode DTC.

at the different speed ranges with quite a change in absolute values, which is a phenomenon that defines the torque ripple variation at high and low speeds. As reported in the DSVM technique, a new switching table set has been established by the use of a multilevel torque hysteresis comparator; the speed range has also been considered [76,77].

3.1.6. DTC using discontinuous PWM

Based on power electronic schemes, a few discontinuous PWM (DPWM) techniques have been proposed. These schemes use Zero sequence signal, which is discontinuous. During a sampling time, one phase halts modulation and accompanied phase clamps to negative or positive DC bus. Therefore, the switching losses of the inverter leg involved are removed. The performance of PWM schemes depends on the modulation index. Continuous PWM (CPWM) schemes are better than DPWM in the low modulation range, however, in the high modulation range DPWM are better than CPWM [78]. As to the overall modulation range, DPWM scheme has lower switching losses than CPWM methods. Using the generalized phase shift in DPWM techniques, a carrier based PWM technique has been introduced in [78–80], which is known as the generalized DPWM (GDPWM). Reddy, in [81], proposed a sensor-less DTC-IM drive using the GDPWM algorithm. Within a sampling interval, an equal division of a zero voltage vector is employed by the conventional space vector PWM algorithm. Zero state time division generally results in various DPWM schemes, and using the freedom of zero state space vector the GDPWM algorithm is developed and initiated. The switching losses of the inverter are minimized by the usage of bus-clamped sequences.

3.2. DTC based on modern control theory

Modern control theories have been broadly used in dynamic and power control systems in past decades. Recently, many DTC controllers have been proposed that combine modern control techniques, such as sliding mode, fuzzy logic and artificial neural network (ANN) with conventional DTC schemes.

3.2.1. Sliding mode(SM) controller

This is a basic concept for a variable structure control (VSC), a control strategy, as shown in Fig. 11, with discontinuity is well suited for a nonlinear dynamic system with uncertainties. This control scheme is fast and robust [82–84] but the controlled quantity exhibits undesirable chattering. DTC for AC drives fed by inverter, in which the inverter states are being selected in accordance with the control errors of torque and flux, can be taken into account as a particular case of the VSC. As a matter of fact, advantage has been derived from the variable structure behaviour of the inverter. In steady state, irregular chattering is typical for controlled torque and flux.

Sliding mode control (SMC) concepts have been researched for DTC-SVM for induction motors [82–88], which are characterized by the insistence of a sliding mode heading to the low sensitivity with respect to parameter variation and disturbances [82,88]. This control scheme improves the steady state performance and preserves the transient advantages [82]. However, the scheme used in [82] does not eliminate the PI controller demerits, such as large overshoot and adjusting time. In [87] a SM method was adopted thereby realizing the control of rotor flux and the torque. If the estimation of the rotor flux is precise then the control technique achieves good steady state and transient performance. However, it is acknowledged that the estimation of rotor flux is affected not only by electrical parameters but also mechanical parameters. Hence, it becomes difficult to achieve better performance in real applications with the particular scheme.

In [88] an attempt has been made to synthesize the direct torque and rotor flux control schemes (DTRFC) using the SM theory. The existence of switches in the voltage source inverter (VSI) amplifies the number of choices in the sliding-mode theory. Variation in the topology of the control systems is a result of the variations in the state of different switches. Analysis of two cases of VSI controls were performed; namely, an indirect control via SVM and a direct control (hysteresis VSI control) by means of a switching table. A new strategy was developed using the two methods for VSI control mentioned earlier. This new control technique is known as dynamic re-configuration of VSI control algorithms. This resulting technique produces low chattering at steady state due to the VSI indirect control strategy and an outstanding dynamic performance at transient state due to the VSI direct control method.

3.2.2. Fuzzy based DTC controller

In 1994, a Fuzzy based DTC (FDTC) controller was first proposed by Mir [89]. In this controller, as shown in Fig. 12, fuzzy logic has

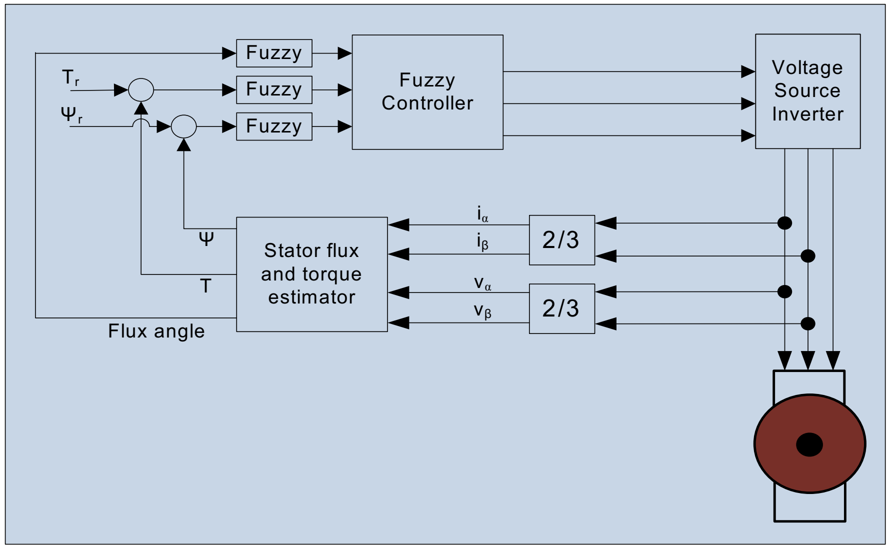

Fig. 12. Fuzzy based DTC.

been used to replace the hysteresis controllers and switching table for selecting the space vector in the conventional DTC-IM drive. The torque and flux errors, and stator flux position are the input to the fuzzy controller. Each sector, which is 60°, has been fuzzified into two subsets, and, also, there is a table of the fuzzy rules in each subset sector, which results in a large number of fuzzy rules.

Later much research concerning fuzzy logic applied to DTC has been carried out [90–97]. In [90] a particular mapping has been used for the stator flux position to reduce the number of rules and increase the controllers speed. It has been proven that it is possible to apply FDTC for AC motor application in which dynamic performance is highly demanded [92]. A fuzzy sliding mode controller (FSMC) is addressed in [37], in which a discontinuous part of the classical SMC control law is replaced by the fuzzy logic controller. As a result, the speed and torque ripple is dramatically reduced and it also gives a fast speed response [91]. In [94,95] fuzzy logic is used to control the lower and upper limit of the torque hysteresis band based on feedback inputs, which results in reduced torque ripple compared to the conventional DTC as well as improved dynamic performance. Variations of stator current and motor speed are used as inputs to FLC. The FLC output is decremental or incremental torque, which will then be added to initially set values of the hysteresis band. A self-tuned fuzzy pi speed controller strategy is proposed in [96] for the DTC-IM drive to improve the performance.

For the DTC drive, fuzzy logic strategy is normally used to get more subdivided vectors to minimize the flux and torque ripples, and, also, sometimes for controlling the speed. There must be a compromise between the fuzzy rules calculation cost and the performance. In addition, it should be taken into account that the whole system should be as simple as possible. However, a fuzzy controller uses many rules based on the extensive experiments. Therefore, it is difficult to implement [98].

3.2.3. Neural network based DTC

ANN applications are favoured for various reasons—their architecture is simple, ease of training algorithm, nonlinear function approximating ability, and also insensitive to disturbances [99]. Recently, artificial neural networks (ANN) have been used for nonlinear dynamic system identification and control in ac drives and power electronics, as it is possible to approximate any nonlinear function with high accuracy [100,101]. Researchers have introduced ANN with DTC for designing controllers, state estimation and parameter identification of the motor control system [99,102–112].

ANN has been addressed in [102,105,106,108,111] to estimate the motor speed, as a result, the drives become speed sensor-less, which reduces the cost of the drive and improves drive performance. Different types of neural network have been used in these controllers, such as feed forward multilayer ANN, and recursive ANN. As vector selection in DTC is complex, and since a simple vector selection strategy using ANN has been proposed in [99,107,110,112] it has been proven that replacing the switching table of a DTC by ANN controller is possible. This gives accurate vector selection, and, as a result, high torque response can be achieved. To reduce the torque ripple of the drive, accurate flux estimation is very important. In the conventional system, the flux estimator uses an integrator, which creates a drift problem. The ANN proposed in [104] can easily estimate flux thereby mitigating the drift problem, and, as a result, an accurate voltage vector can be selected, which improves the drive performance.

3.2.4. New Trends of DTC drive

Currently, many researchers are looking into the development of DTC techniques combining two or three of the techniques stated above. As noted, the VSC and FDTC controller perform well but they have some limitations, such as errors in parameter estimation and nonlinear uncertainties. Moreover, ANN is widely used to estimate and observe stator resistance and motor state [113–116], however, there are a small number of uses of DTC drive using ANN because training the neural network online is very hard without a perfect controller.

A DTC-IM drive using neuro-fuzzy controller has been presented in [97,117] to adjust the hysteresis band limit online to reduce the torque ripple and improve the drive performance. The scheme proposed in [117], as shown in Fig. 13, the error signals ε_ψ and ε_T are worked as input to the neuro-fuzzy controller (NFC), which also uses stator flux position information. The NFC controller determines the stator voltage vector in the polar coordinates $\boldsymbol{v_c} = [V_C\ \varphi_{Vc}]$ for voltage modulator, which generates pulses ($S_a\ S_b\ S_c$) to the control inverter. Combining both ANN and fuzzy logic allow to achieve all of the benefits of both systems. This scheme is thus characterized not only by good dynamic and steady state performance, but also by a simple self-tuning procedure.

To reduce the torque ripple of the motor drive, some researchers introduced a matrix converter [118–130] and multilevel inverter

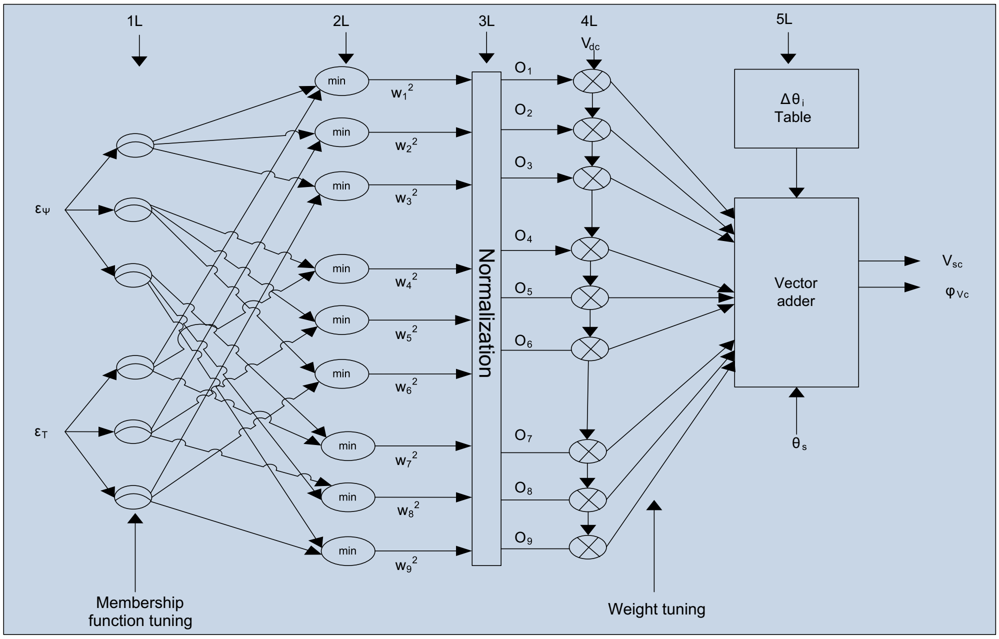

Fig. 13. Neuro-fuzzy controller [115].

Table 2
Critical analysis of different control method of DTC IM drive.

Control method	Indicators				
	Control complexity	Torque and flux response	Precession	Switching loss	Computational time
Scalar control	Simplest	poor	Lowest	Low	Low
FOC	Complex	Medium	High	Medium	High
DTC	Simple	Fast	Low	High	Low
DTC-SVM	Simple	Fast	Medium	Low	High
DTC-SVM (discreet)	Simple	Fast	Medium	Medium	Medium
DTC-SMC	Complex	Fast	Medium	Medium	High
DTC-FLC	Complex	Fast	Medium	Medium	High
DTC-ANN	Complex	Fast	Medium	Medium	High
DTC-NFC	Complex	Fast	High	Medium	High
DTC-FSTPI	Simple	Fast	Medium	Low	low
DTC-MC	Complex	Medium	Medium	High	Medium
DTC-MLI	Complex	Fast	High	High	High

[131–135] in the induction motor drive application to replace the conventional two level voltage inverter. The advantage of using a matrix converter and multilevel inverter is that it is possible to use a higher voltage vector, which, consequently reduces the torque ripple of the drive and improve the system performance. However, more switches are used in this system, which increases the system cost.

In [40,136,137] a four-switch three-phase inverter (FSTPI) fed IM drive has been proposed, which is based on the emulation of a six-switch three phase inverter (SSTPI) fed IM drive operation. It has been revealed that the proposed DTC exhibits high performance compared to the SSTPI fed IM drive. As the proposed scheme uses only four switches instead of six the overall system cost is also reduced.

To make the system cost effective and also increase the performance of the drive, in [138,139], a new technique for DTC-IM drive is proposed, which uses a single current sensor inserted in the inverter dc link. A DC current is used for constructing the stator current required for estimating the motor torque and flux. This technique is robust and simple.

Although modern control schemes can give a good solution for nonlinear systems, there are still some limitations that hamper the building of an ideal motor drive with any of the modern control schemes on their own. Therefore, a combination of two or more control techniques in a drive system for handling uncertain errors and parameter variation to get good performance is required. A summary of the above mentioned control strategies for the DTC IM drive is tabulated in Table 2.

4. DTC application

Nowadays energy conservation and environmental safety are of great concern. In these circumstances EV technology development has taken an accelerated pace to achieve these requirements. Concerning the environment, EVs can deliver emission-free urban transportation [140].

The heart of EV is the electric propulsion system [141], which consists of a motor drive, wheels, and transmission device, as given in Fig. 14. The motor drive is designed in such a way that it can respond to the demanded torque, which is set by the driver. Usually, DC motors are used in EV because of their suitable torque-speed characteristics for traction requirement and simple speed control strategy. Recently, IMs have been extensively acknowledged for EV propulsion due to their robustness, high reliability and low maintenance requirements.

With the aim of improving the dynamic performance of IMs for EV propulsion, DTC has gained attention [142–144] due to its fast torque response and lack of heavy on-line computation compared to FOC. Also, a high current ripple is produced in FOC, which affects the system efficiency. In [145,146] DTC-SVM is implemented in EV. Based on the SVM technique conventional DTC can overcome various shortcomings, including torque ripple, electromagnetism noise and current harmonics, while retaining the merits of the FOC.

However, DTC-SVM requires online calculation of a number of complicated equations, and is influenced by more parameters of the motor. Casadei et al. [147] addressed DTC using the DSVM scheme, which reduces torque and ripple without increasing the complexity of the traditional DTC, as proven in Ref. [148].

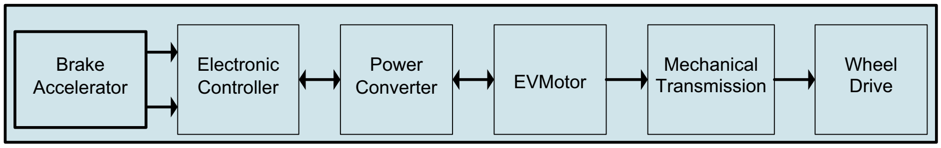

Fig. 14. EV compositions.

In [149] it has been proved that a significant reduction of torque, flux and current ripple has been achieved using direct-torque fuzzy control (DTFC) based on SVM suitable for EV application compared with traditional DTC using a three level inverter.

The direct torque neuro fuzzy control (DTNFC) proposed in [150] shows fast torque response, as well as low torque and current ripple. The proposed DTNFC uses an ANFIS structure, which is automatically tuned by a BP algorithm for output and input membership functions along with the least-square estimation for output membership functions. The preferred flux and torque are acquired. The hybrid MLI proposed in [151,152] provides a DTC solution for high power drives, not only for the capability of the higher voltage provided by MLIs, but also because of the reduced switching loss and improved quality of output voltage, which gives a sinusoidal current without an output filter.

IMs drives are comparatively low-cost, reliable and maintenance free when used as dc motors, however, their usage is minimal in intelligent manufacturing technology and MEMS because of complications with their positioning and control. Nevertheless, because of recent progress in high speed processors like DSPs and power semiconductor switches, they have become good enough to be used in aerospace and robotics, etc. DTC-IM drives are well suited for applications in industrial manipulator drives with positioning and high dynamical requirements. The implementation of robust control greatly reduces the error in trajectory tracking, which is approximately 8 to 10 times [153] in contrast to classical controllers. An absolute leader in trajectory tracking is the dynamic state robot controller. The preeminent control ability is achieved by coupling the correction signal with robust control. Better control is attributed by higher switching than lower frequency switching. In these circumstances, the DTC-IM drive is highly recommended for use in Micro-Electro-Mechanical Systems (MEMS) and intelligent manufacturing systems as DTC ensures the decoupled control of flux and torque [154]. Techometer is not needed in 95% of all industry applications of DTC drive which minimize the investment cost and increase the reliability [155]. About 75% of total energy is consumed in the industrial sector is due to the electric motors. Around two thirds of the industry motors are used in pumps ad fans which do not required constant motor speed [156]. Applying the DTC scheme motor can be controlled at any required speed as dynamic response of the DTC drive is very fast [157] which can help to save significant amount of energy.

In [158] the DTC scheme is implemented in railway traction for the entire speed range. With a U-N based stator flux observer, the selection of voltage vector, traction start-up, good dynamic and steady state performance of the railway traction is attained in the low speed range. To get high dynamic performance in the high speed range, the flux regulation method is addressed under the square wave condition. The close loop torque control method based on flux regulation is given, which improves the dynamic and steady state performance of railway traction.

In the last two decades wind energy utilization has been increased rapidly due to the increasing concerns on energy crisis as well as environmental pollutions. Variable-speed wind turbine generators (WTGs) have attracted great interests because of their high energy production efficiency and low torque spike. Maximum wind energy can be captured by adjusting the shaft speed in such systems [159]. A SVM-DTC scheme is proposed in [159] which uses the MPPT control algorithm to make the system sensorless. Resultant SVM-DTC regulated wind turbine achieved maximum power extraction, fast torque response and also torque and flux ripple is reduced [159].

Reliability and availability levels are very important aspects to assess the economic viability of wind energy conversion systems (WECSs) [160]. WECSs are normally located in rural areas with weak grid connection where grid voltage can be unbalanced even in normal operation which produce torque pulsation. It will result in acoustic noise at low level and damage the rotor shafts, gear boxes and blades at high level [161]. A SVM based integral sliding-mode direct torque control (ISM-DTC) scheme for wind energy conversion systems is proposed in [162] under unbalance grid voltage which reduces the ripples in active power, reactive power or torque.

5. Conclusion

All over the world a significant amount of energy has always been consumed by the induction motor drives. Thus, global electricity financial savings can be carried out when ASD is utilized to replace the majority of the existing nonadjustable drive systems for IM. Proper control of the motor can reduce loss as well as improve the efficiency of the drive system.

An extensive review of DTC schemes for IM drives is presented in this paper. Although DTC is cost effective compared to FOC because of its simplicity and robustness, there are some drawbacks, such as flux and torque ripple. From the survey it can be seen that although many DTC schemes have been proposed to improve the drive performance, to date, there are still some limitations. However, by combining two or more modern techniques, drive performance can be improved and a low cost system can be achieved. Combining these techniques DTC drive can be used effectively in renewable energy conversion systems and electric vehicle and also in the industrial sector to minimize energy losses.

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